Energy & Buildings 173 (2018) 38–44

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Different responses of cooling energy consumption in office buildings to climatic change in major climate zones of China

Mingcai Li[a,*], Jingfu Cao[a], Mingming Xiong[a], Ji Li[b], Xiaomei Feng[b], Fanchao Meng[a]

[a] Tianjin Climate Center, No. 100 Qixiangtai Road, Hexi District, Tianjin 300074, PR China
[b] Institute of Building Environment and Energy Efficiency, China Academy of Building Research, Beijing 100013, PR China

ARTICLE INFO

Article history:
Received 21 February 2017
Revised 12 May 2018
Accepted 20 May 2018
Available online 24 May 2018

Keywords:
Energy consumption
Cooling load
Climate change
Different climate zones
Climatic parameters

ABSTRACT

This paper investigates the climate change impact on cooling energy consumption of office buildings in four major architectural climate zones in China. The results show that there are apparent differences in the responses of monthly or yearly cooling loads to climatic change in different climates. Dominant factors affecting monthly cooling loads change from dry bulb temperature (DBT) to wet bulb temperature (WBT) with the climate zones changing from severe cold to hot. The yearly cooling load was mainly afftectd by DBT in severe cold climate, whereas the WBT had the dominant effect in the other climates. With the continuous warming climate, the yearly cooling load did not rise significantly for any climate zone except for severe cold climate zone where cooling load had a significant increase ($p < 0.01$). More importantly, the cooling load showed a weak decrease in Guangzhou. These results suggest that different measurements for buildings cooling energy conservation should be made in different climate zones. The humidity effect should be fully considered to improve buildings energy efficiency, especially in the hot climate zones. The continuous increase of temperature in the future does not necessarily increase cooling loads of buildings in the cold, hot summer & cold winter and hot summer & warm winter climate zones, and change trendency of humidity in the future need to be considered to predict cooling energy consumption.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

According to the fifth assessment report of the Intergovernmetnal Panel on Climate Change (IPCC), compared to the values from 1850 to 1900 the global surface temperature increased 0.85 °C during 1880–2012 and increased 0.78 °C during 2003–2012 [11]. In addition, as the global warming continues, temperatures in the years 2081–2100 are projected to increase 0.3 °C–4.8 °C from those recorded in 1986–2005, depending on emissions scenario and climate model [11]. This global warming strongly affects the diversity of human society and the natural world. Energy use, being of fundamental importance for society, has received wide concern, especially about the environmental implications of energy use [29]. To date, buildings in developed and developing countries consume >40% of total energy consumption and produce approximately 33% of global greenhouse gas emissions [32]. This increasing energy consumption, especially in large cities, is related to accelerated urbanization and increasing population size combined with increased comfort level demands [24]. In addition, the increase in energy consumption or demand is, to a large extent, also due to the continuous warming of the climate. Within rapidly urbanized settings, improving the energy efficiency of buildings in response to climate change is one of the main methods of reducing the rising rate of energy consumption and carbon emissions [16]. Many previous studies have revealed the impacts of climate change on energy consumption or demand and proposed strategies to cope with climate change by improving energy efficiency (e.g., [8,16,20,21,29]).

In China, buildings have also played an important role in the energy demand sector because building energy consumption accounts for more than 30% of the total national energy consumption, a figure that is projected to increase to 35% by 2020 [2,29,31]. One of the environmental problems associated with energy consumption is carbon emission [31]. Since 1986, when the 1st building code was introduced in China, many efficient measures have been made to improve the energy efficiency of buildings [31]. However, energy efficiency in China is still very low compared to the other countries with similar climate conditions to China [31]. In particular, heating or cooling energy consumption which accounts for up to 65% of total building energy consumption in China is much higher than it is in the developed European countries [2].

* Corresponding author.
E-mail address: li_mingcai@163.com (M. Li).

https://doi.org/10.1016/j.enbuild.2018.05.037
0378-7788/© 2018 Elsevier B.V. All rights reserved.

This lower energy efficiency (i.e., higher energy consumption) is, to some extent, related to the lack of detailed information on the impact of climate change on the energy consumption or demand of buildings [16], which partly affecting the establishment of building energy efficient strategies or standards corresponding to changing outdoor meteorological conditions. Therefore, efficient energy saving measures or decision making for selecting HVAC devices under the conditions of climate change or variability can not be fully taken to decrease energy consumption.

The average surface temperature of China increased 1.09 °C during the 1901–2014, which is slightly higher than that of the global average. The incremental rise in temperature is even more apparent in large cities due to the urban heat island effect in regions with increasing population and built-up area [13,26,28]. According to the previoius studies, this has huge implications for energy consumption and the environment [2,18,31]. Building professionals and policy makers have seen the importance of fully considering the impacts of climate change on energy consumption to improve the energy efficiency design in buildings and to reduce energy consumption. Therefore, it is essential to understand to what extent the climate change affects building energy consumption, especially for heating or cooling energy use. However, current understanding of the responses of building energy use to climate change or variability is still rather limited in China [16,19,29]. Some previous studies used degree-days to quickly estimate the climate change impacts on energy consumption for building heating or cooling [4,14]. However, since degree-days are defined as the accumulated degree deviations from a predefined base temperature without considering other climatic parameters (e.g., humidity, radiation, wind speed), their results insufficiently estimated energy consumption or deviated greatly from the restuls of energy simulations [17,30]. Yao et al. [31] also noted that local regulation duplicates the content of national laws, and thus do not draft local energy efficiency regulations. Due to this lack of local jurisdiction and incomplete consideration of local climate change, a large gap in energy-efficient building design between China and the developed countries of the world still exists. Previous studies have revealed that the impact of climate change will vary greatly according to geographical region and building types [30]. It is thus necessary to emphasize the impact of climate change on building energy use within different climates to save energy and reduce greenhouse gas emissions in China.

In the present study, air-conditioned office buildings were selected in different climate zones across China because office building development is one of the fastest growing areas in the building sector during the process of urbanization, especially in large cities such as Beijing, Tianjin, Shanghai and Guangzhou. The energy consumption for air-conditioning (i.e., cooling load) during the years of 1961–2010 was simulated with a simulation tool (transient system simulation program (TRNSYS)). The relationships of cooling load with climatic parameters and the yearly change trend of cooling load were also determined. The aims of the study were (1) to determine the effects of climatic parameters on monthly and yearly cooling loads, and (2) to investigate whether there are different response patterns for cooling energy consumption under different climates.

2. Methodology

2.1. Study area

There are five major architectural climate zones in China: severe cold, cold, hot summer & cold winter, hot summer & warm winter, and mild zones. It should be noted that there are no heating or cooling loads in the mild zone and the heat transfer coefficient (HTC) of building envelops has no limit. Therefore, the mild zone is not included in the present study. Harbin, Tianjin, Shanghai and Guangzhou were selected to represent the four major architectural climate zones (Fig. 1). These four cities range from low to high latitudes (23.0 °N–45.5 °N) with a longitudinal range of 113.1 °E–126.3 °E. In these four cities, Harbin and Tianjin are repectively the second largest cities in the severe cold and cold climate zones and Shanghai and Guangzhou are respectively the largest cities in the hot summer & cold winter and hot summer & warm winter climate zones.

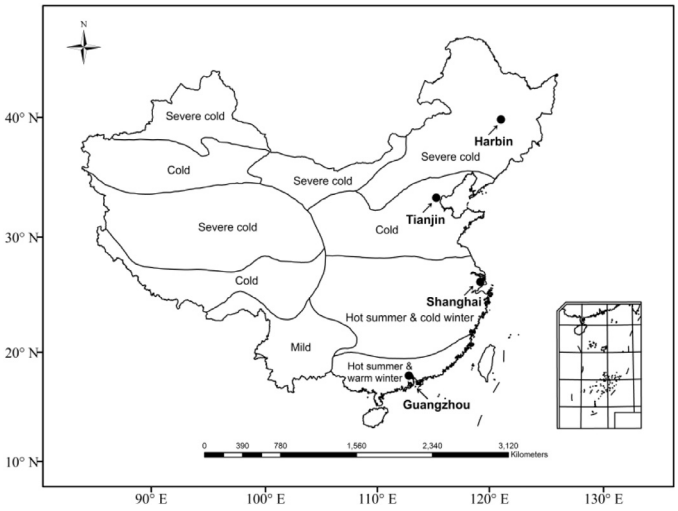

Fig. 1. Overall view of the five major climates and geographical distribution of the selected representing cities.

2.2. Selection of buildings

Generally, office building, as one type of the public buildings, accounts for the largest proportion of the building energy consumption, especially for heating and cooling energy consumption [2]. On a per unit floor basis, energy use in office building with full air-conditioning can be 10–20 times that in residential buildings; thus, office building has large saving potential in terms of energy consumption by considering the climate change impacts [15,29,35]. In this study, a generic and fully air-conditioned office building corresponding to building energy efficient standards and codes in different climate zones across China was used to obtain the cooling load by simulating with TRNSYS software. It is necessary to note that a generic office building in different cities rather than existing buildings was chosen because merely 50% of existing buildings were designed and built by complying with the energy efficient standards [2]. The generic office buildings with simplified envelope and design parameters complying with different energy efficient standards in different climate zones may be beneficial to reveal the impacts of climate change on cooling energy consumption. The design conditions of the buidlings, such as the building envelope HTC, indoor design conditions, and internal load density, were made according to Design Standard for Energy Efficiency in public buildings [7]. In the present study, a 22-story office building with a total area of 12,552 m^2 and a total height of 98 m was selected for the energy consumption simulation. In this study, generic building envelopes and heating, ventilation and air-conditioning (HVAC) designs were carried out based on the prevailing architectural and engineering practices as well as local design/energy codes in the four cities. A summary of the key design parameters is shown in Table 1.

Table 1
Design data for the selected office building in different climate zones of China.

	Building envelope HTC (W m^{-2} $°C^{-1}$)			Indoor design condition Summer/winter			Internal load density			Window-to-wall ratio			
	Wall	Roof	Floor	T(°C)	RH (%)	ACR(1/h)	Occupancy (m^2/person)	Lighting (W/m^2)	Equipment (W/m^2)	East	South	West	North
Harbin	0.45	0.35	2.00	26/20	60/30	1.5	4	11	20	0.27	0.35	0.27	0.26
Tianjin	0.60	0.55	1.50	26/20	60/30	1.5	4	11	20	0.34	0.40	0.34	0.41
Shanghai	1.00	0.70	1.20	26/20	60/30	1.5	4	11	20	0.45	0.50	0.45	0.42
Guangzhou	1.50	0.90	1.00	26	60	1.5	4	11	20	0.51	0.62	0.51	0.50

2.3. Multi-year simulation of building energy consumption

Energy consumption simulations were carried out using the TRNSYS software. TRNSYS is a transient system simulation program with a modular structure designed to solve complex energy system problems by breaking them down into a series of small components [10]. Building energy consumption simulaition is an accepted and widely used analytical technique, although there are always differences between simulated results and actual energy consumption [29]. In a comparative energy consumption study, the simulation method gives a good indication of the likely percentage change and any underlying trend in the data [29]. To accomplish the energy consumption simulation, two types of inputs were needed. Building parameters above (Table 1) were first inputted through a dedicated visual interface.

In addition to the building input data, a weather data base was also built into the software as an input file. To obtain the hour-by-hour energy consumption during the 1961–2010, hourly data for multiple climatic variables including dry bulb temperature (DBT), solar radiation (SR), wet bulb temperature (WBT), wind direction (WD) and wind speed (WS) were inputted into the TRNSYS software. The metetological data are from the National Meteorological Information Center. To obtain the information of climate change impacts on energy consumption in the central urban area, the meteorological observation stations (with longer history records) located in the urban center of the four cities were selected (the meteorological observation stations in Harbin, Tianjin and Guangzhou belonging to the national basic meteorological stations of China, and the station in Shanghai being a general meteorological station). The quality control and the homogeneity of the selected meteorological data have been strictly tested to ensure reliability and accuracy of the data. Generally, station relocation is one of the most important factors that cause the discontinuities in temporal series of meteorological data. In Previous studies, the RHtestsV3 combined with station metadata was used for homogeneity test of meteorological data to ensure the reliability and accuracy and found that no apparent discontinuities are detected for these selected meteorological data and the data are relatively reliable ([3], Meng et al. 2018).

WS and WD were directly collected from the observed data. DBT and relative humidity (RH) recorded four times per day during the period of 1981–2005/2006 (with hourly records since approximately 2006) were used to generate hourly data by using the cubic spline interpolation method and then WBT was obtained by the corresponding DBT and RH. Hourly SR was first generated from the daily total SR by using the Collores-Perein and Rabl Model [27]. Generated hourly SR data were then adjusted for rainy, foggy and sunny weather conditions. Our early work has confirmed the reliability of the calculated data [16].

2.4. Statistical analysis

Due to the high inter-correlation of meteorological variables, multiple stepwise linear regressions were used to identify the dominant variables affecting the building energy consumption. Briefly, multiple stepwise linear regressions on the monthly and yearly cooling loads were performed against the possible climatic parameters (i.e., mean temperature, maximum temperature (MAT), minimum temperature (MIT), WBT, SR, and WS) in the cooling period. Linear regression analysis was also performed to examine yearly variations of the cooling load; correlation analysis was used to study the relationship between yearly cooling load and corresponding climatic parameters. Statistical analyses were performed using SPSS 16.0 for Windows, and significance levels were set at $p < 0.05$.

3. Responses of cooling load to climatic parameters

3.1. Monthly cooling load

There were apparent differences in the responses of monthly building cooling loads to corresponding climatic parameters in the four climate zones (Table 2). For the selected office building in Harbin, the cooling load was predominantly affected by the DBT in June and August, which explained more than 83% of the variations of the monthly cooling load ($R^2 = 0.83–0.94$), whereas in July it was dominantly affected by the WBT ($R^2 = 0.80$). For Tianjin, the monthly cooling load was predominantly affected by the DBT in June and September ($R^2 = 0.54–0.65$) but by the WBT in July and August ($R^2 = 0.78–0.81$). In Shanghai, the WBT was the dominant affecting parameter for average monthly cooling load ($R^2 = 0.88–0.90$) except for that of June, which was dominantly affected by the DBT ($R^2 = 0.84$). Finally, in Guangzhou, each month's cooling load was mainly dominated by the WBT ($R^2 = 0.77–0.81$). When the monthly cooling load data were pooled across the whole cooling season, the DBT was the dominant affecting parameter in Harbin ($R^2 = 0.87$), whereas in the other three cities cooling loads were dominantly affected by the WBT ($R^2 = 0.78–0.96$).

3.2. Yearly cooling load

During 1961–2010, the four cities in different climate zones have different patterns in their yearly building cooling loads. The yearly cooling load in Harbin significantly increased from 1961 to 2010 at a rate of 3.8 W/m^2 ($p < 0.01$, Fig. 2). There was no apparent change trends for the yearly cooling loads in Tianjin and Shanghai ($p > 0.05$, Fig. 2). In contrast, during the period of 1961–2010, the yearly cooling load in Guangzhou had a weakly significant decrease rate of 2.1 W/m^2 at the 90% significant confidence level ($p = 0.072$, Fig. 2).

The dominant climatic parameters affecting the cooling load were shown in Table 3. Of the four parameters that were entered into the regression models, the DBT was the predominant factor ($R^2 = 0.83$) in Harbin, with smaller contributions of the WBT and SR. The WBT and SR in Tianjin were the two dominant climatic parameters affecting the yearly cooling load ($R^2 = 0.93$), suggesting that the combination of these two parameters could explain over 93% of the cooling load. For the yearly cooling load in

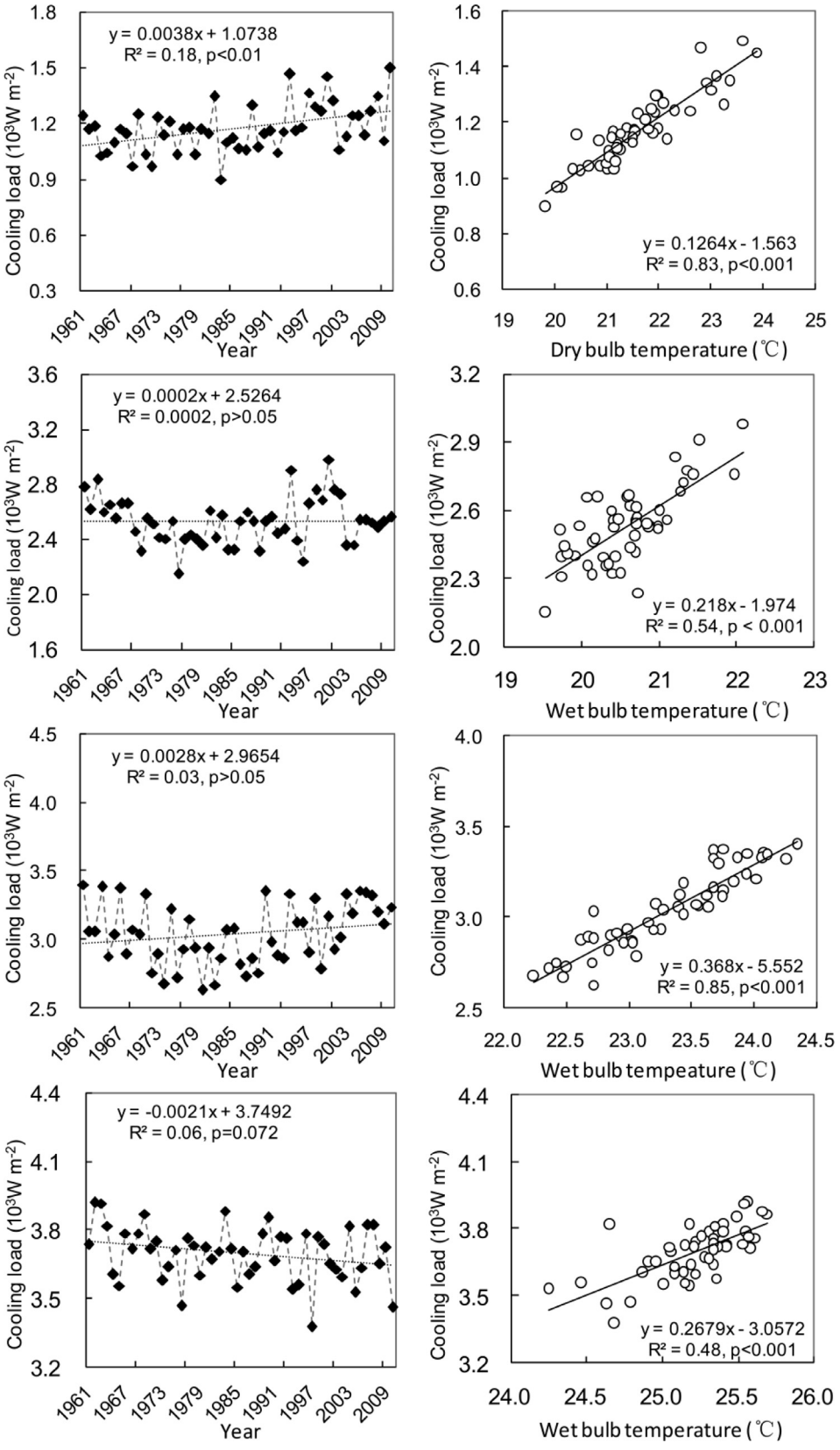

Fig. 2. Yearly changes in the cooling load of an office building (left) and its relationship with the average dry bulb temperature or wet bulb temperature (right) in the four cities.

Table 2
The first climatic parameter entering the regression models according to stepwise multiple linear regression of the monthly cooling load against the climatic parameters. R^2 represents the adjusted determination coefficient, and ***indicates a significance of $p < 0.001$.

	Harbin		Tianjin		Shanghai		Guangzhou	
Cooling season	DBT	0.87***	WBT	0.92***	WBT	0.96***	WBT	0.78***
June	DBT	0.94***	DBT	0.54***	DBT	0.84***	WBT	0.77***
July	WBT	0.80***	WBT	0.81***	WBT	0.88***	WBT	0.80***
August	DBT	0.83***	WBT	0.78***	WBT	0.89***	WBT	0.79***
September	–	–	DBT	0.65***	WBT	0.90***	WBT	0.81***

Note: DBT, dry bulb temperature; WBT, wet bulb temperature.

Table 3
Stepwise multiple linear regression of the yearly cooling load for the office building against the climatic parameters. Adjusted R2 are given, and ***indicates a significance of $P < 0.001$.

		One-factor model	Two-factor model	Three-factor model
Harbin		126.425 × DBT	87.868 × DBT	64.265 × DBT
			76.916 × WBT	101.859 × WBT
				24.021 × SR
	Constant	−1562.96	−2119.069	−2494.188
	R^2	0.836***	0.913***	0.970***
Tianjin		218.746 × WBT	246.002 × WBT	195.471 × WBT
			62.183 × SR	59.949 × SR
				52.772 × DBT
	Constant	−1973.765	−3604.923	−3830.007
	R^2	0.545***	0.930***	0.962***
Shanghai		368.573 × WBT	344.788 × WBT	263.087 × WBT
			49.88 × SR	50.731 × SR
				52.258 × DBT
	Constant	−5552.499	−5791.392	−5548.591
	R^2	0.852***	0.978***	0.992***
Guangzhou		267.897 × WBT	275.199 × WBT	
			70.685 × DBT	
	Constant	−3057.198	−5119.135	
	R^2	0.488**	0.577***	

Note: DBT, dry bulb temperature; WBT, wet bulb temperature; SR, solar radiation; MIT, minimum temperature.

Shanghai, the WBT was the dominant affecting factor ($R^2 = 0.85$) and SR had a minor contribution (Table 3). For the yearly building cooling load of Guangzhou, only two climatic parameters entered the regression models; WBT was the dominant factor ($R^2 = 0.48$), with small contribution from the DBT (Table 3). According to the effects of dominant climatic parameters on cooling load, the 1 °C effect can be made. With an increase of 1 °C in DBT, the cooling load in Harbin will increase by 126.4 W/m^2 (Fig. 2). In Tianjin, Shanghai and Guangzhou, the cooling load will increase by 218.0 W/m^2, 368.0 W/m^2 and 267.9 W/m^2, respectively, with an increase of 1 °C in the WBT (Fig. 2).

4. Discussion

According to previous studies, building energy consumption is inevitably related to climate as well as to socio-economic factors including economic growth and increasing urbanization and population [2,12,25]. Therefore, the socioeconomic impacts on energy consumption should be removed to determine the climate effects [25]. At present, there are two dominant methods for determining the climate/climate change impacts on building energy consumption for heating or cooling: degree-days [1,5,14] and energy consumption simulation by software [16,18,19,23,29]. The reason that the degree-days method is widely used to reveal the effects of climate change on energy consumption is because degree-day variables have significant power in describing historic change in building energy demands [14,21,23,33]. In this study, the unit area energy consumption for heating or cooling (expressed as heating or cooling loads) was simulated by TRNSYS by inputting building and meteorological parameters. The impacts of climate change on cooling load can be quantified with the variable climatic parameters and constant building parameters [16].

The present study revealed that there are apparent monthly differences in the responses of building cooling loads to climatic parameters, especially between the north and the south of China, i.e., the extreme cold, cold, hot summer & cold winter, and hot summer & warm winter climate zones. The dominant climatic parameters affecting cooling load change from the DBT to the WBT with the changes from the extreme cold to warm climates. In addition, it necessary to note that although the DBT dominantly affects in most months, the cooling load in July (i.e., the middle of the summer) is mainly affected by the WBT in Harbin. Similarly, the cooling loads of July and August in Tianjin, July, August and September in Shanghai, and all the months in Guangzhou are also dominantly affected by the WBT. This means the high cooling energy consumption is dominantly related to the temperature in relatively cool or transitional seasons. However, in addition to temperature, humidity should also be fully considered to explain the cooling energy consumption in hot seasons, especially given the possibility that the combination of temperature and humidity may cause higher cooling energy consumption. In previous studies, the cooling or heating degree-days were used to determine the impacts of climate change on building energy consumption because it can quantify only the impact of temperature. However, this study suggests that only in the north of China or in the cooling season single temperature is the dominant factor affecting cooling energy consumption. Within the hot climates or in the hot season, the humidity should also be fully considered. Therefore, using the degree-days method (defined as the accumulated degree deviations from a predefined base temperature without considering other climatic parameters) may partly lead to insufficient estimation of building heating or cooling energy demand [17].

According to previous studies, energy consumption, or demand for cooling and heating are expected to increase and decrease, respectively, due to continuous climate warming (e.g., [14,18,29,30]). Consistent with these studies, the yearly cooling load in the extremely cold climate of Harbin significantly increased during the last 50 years along with the warming of the climate. However, the cooling loads in Tianjin, Shanghai, and Guangzhou, located in other climates, did not show any significant increase during 1961–2010. Instead, the yearly cooling load in Guangzhou weakly but significantly decreased at the 90% confidence level ($p = 0.07$). These results suggest that, under global or local climatic warming conditions, cooling energy consumption does not always display an increasing trend. The cooling load has a close relationship with the DBT ($r^2 = 0.83$) in Harbin; the significant increase in DBT (0.34 °C/10 yr) directly leads to an increase in cooling energy consumption. The major reason for the lack of a singificnat increase in the cooling loads in Tianjin, Shanghai and Guangzhou is that the WBT did not rise during the period of 1961–2010. In addition, the WBT of Guangzhou showed a significant decrease in the last 50 years (0.07 °C/10 yr), especially from 1993 to 2010 (decreasing 0.35 °C/10 yr), causing the decrease of the cooling load. Generally, the DBT generally affects the sensible load, while latent load is affected by humidity [6]. Humidity has decreased significantly in all four of the cities, with the decreasing rates of 0.82%, 1.29%, 1.76% and 1.87% in Harbin, Tianjin, Shanghai and Guangzhou, respectively. Thus, the results suggest that in these cities, especially Guangzhou, gradually reduced cooling loads were required to provide thermal comfort during the period of 1961–2010. The major reason for this is that the energy consumption needed for dehumidification will decrease along with the decrease of WBT or humidity. According to the present results, the changes of DBT and WBT, especially those variations dependent on different climates or months, should be fully considered when developing different building energy-saving technologies or measures. In hot seasons with high humidity, air-conditioning systems should be designed not only for decreasing temperature but also for dehumidification to achieve comfortable conditions. The results are not only helpful for efficient design of air-conditioning systems but also provide some references for the office building design under the changing climate in the past or the future. For example, in Guangzhou, Shanghai and Tianjin, the HTC of building envelope may not decrease with the increasing of the temperature difference between exterior and interior design conditions because the rise of single temperature does not contribute to the increase of energy consumption. By contrast, shading, especially window shading by decreasing windor-wall ratio (WWR) or changing the orientation of office buildings in the hot summer climate zones should be fully considered to reduce heat gain in summer, especially through south orientation. For the office buildings in Harbin in severe cold climate zones, WWR should be increased with decreasing the HTC of window under the continuing climate warming to increase heat gain in winter because the reduction rate of heating energy consumption in winter (14 W/m^2, [22]) is largely more than increase of energy consumption in summer (3.8 W/m^2).

The relationships between energy use and climatic parameters can be generally used to predict energy consumption under future climatic conditions, which is beneficial for optimizing the operational mode and improving the comprehensive energy efficiency of heating or air-conditioning systems [8,16]. Long-term prediction of energy consumption is required for making decisions about energy scheduling and supply strategies [9,34]. According to the present study, monthly and yearly cooling loads can be well predicted by single or multiple climatic factors based on regression models. The 1 °C effect for the annual energy consumption can be determined based on the dominant effect of DBT or WBT on energy consumption during the cooling period. An 11.6% increase in cooling load is found with a 1 °C increase in DBT in Harbin, whereas a 1 °C increase in WBT causes an 8.3%, 14.4% and 7.9% increase in cooling loads in Tianjin, Shanghai and Guangzhou, respectively. Based on the relationship of cooling load to climatic parameters and the trend of increasing temperatures, continuous climate warming in the future could result in the increase in energy consumption for cooling in Harbin and therefore the appropriate expansion of air-conditioning devices to meet cooling demand. By contrast, in other cities, the future cooling energy consumption per unit area may not undergo apparent change or may even decrease in the hot climate zone, which is beneficial for saving energy by changing the capacity of air-conditioning systems.

In summary, the impact of climate change on the monthly and yearly cooling loads for office buildings in four climate zones was estimated. The results reveal that the responses of monthly or yearly cooling loads to climatic change are dependent upon different climates. This means that different measures for building cooling energy conservation should be used according to different climates. The effect of humidity especially needs to be fully considered to improve the building energy efficiency in the southern cities of China. The monthly and yearly cooling loads can be well predicted by their relationships with climatic parameters. Particularly, the possible increasing temperatures in the future may not result in the increase of cooling loads in southern China, because the energy consumption needed for dehumidification will reduce. The results are helpful for saving energy and improving comfort conditions by allowing workers from different regions to select more appropriate cooling devices.

Conflict of interest

The authors declared that they have no conflicts of interest to this work.

Acknowledgements

This work was financially supported by the Climate Change Special Funding (CCSF201831, CCSF201614) project of the China Meteorological Bureau.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2018.05.037.

References

[1] A.D. Amato, M. Ruth, P. Kirshen, J. Horwitz, Regional energy demand responses to climate change: methodology and application to the Common wealth of Massachusetts, Clim. Change 71 (2005) 175–201.
[2] W.G. Cai, Y. Wu, Y. Zhong, H. Ren, China building energy consumption: situation, challenges and corresponding measures, Energy Policy 37 (2009) 2054–2059.
[3] J.F Cao, M.C. Li, M. Wang, M.M. Xiong, F.C. Meng, Effects of climate change on outdoor meteorological parameters for building energy-saving design in the different climate zones of China, Energy Build. 146 (2017) 65–72.
[4] L. Chen, X.Q. Fang, S. Li, Impacts of climate warming on heating energy consumption and southern boundaries of severe cold and cold regions in China, Chin. Sci. Bull. 52 (2007) 2854–2858.
[5] M. Christenson, H. Manz, D. Gyalistras, Climate warming impact on degree–days and building energy demand in Switzerland, Energy Convers. Manag. 47 (2006) 671–686.
[6] S. Delfani, M. Karami, H. Pasdarshahri, The effects of climate change on energy consumption of cooling systems in Tehran, Energy Build. 42 (2010) 1952–1957.
[7] DSEE, Design Standard for Energy Efficiency in Publich Buildings GB 50189-2005, China Architecture and Building Press, Beijing, 2005. (in Chinese).
[8] M. Dolinar, B. Vidrih, L. Kajfez-bogataj, S. Medved, Predicted changes in energy demands for heating and cooling due to climate change, Phys. Chem. Earch 35 (2010) 100–106.
[9] L. Ekonomou, Greek long-term energy consumption prediction using artificial neural networks, Energy 35 (2010) 512–517.

[10] D.B. Grawley, J. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Build. Environ. 43 (2008) 231–238.
[11] IPCC, Summary for policymakers of climate change 2013: the physical science basis, Contribution of Warking Group I to the Fifth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, Cambridge, 2013.
[12] M. Isaac, D.P. van Vuuren, Modeling global residential sector energy demand for heating and air conditioning in the context of climate change, Energy Policy 37 (2) (2009) 507–521.
[13] V. Jankovic, M. Hebbert, Hidden climate change-urban meteorology and the scales of real weather, Clim. Change 113 (2012) 23–33.
[14] F.Q. Jiang, X.M. Li, B.G. Wei, R.J. Hu, Z. Li, Observed trends of heating and cooling degree-days in Xinjiang Province, China, Theor. Appl. Climatol. 97 (2012) 349–360.
[15] J. Lam, K.K.W. Wan, D.L. Liu, C.L. Tsang, Multiple regression models for energy use in air-conditioned office buildings in different climates, Energy Convers. Manag. 51 (2010) 2692–2697.
[16] M.C. Li, J.F. Cao, J. Guo, J.D. Niu, M.M. Xiong, Response of energy consumption for building heating to climatic change and variability in Tianjin City, China, Meteorol. Appl. 23 (2016) 123–131.
[17] M.C. Li, J. Guo, J. Shi, M.M. Xiong, Applicability evaluation of cooling/heating degree-days in analyzing building energy consumption changes, Clim. Change Res. 9 (1) (2013) 43–48. (in Chinese with English abstract).
[18] M.C. Li, J. Shi, J. Guo, J.F. Cao, J.D. Niu, M.M. Xiong, Climate impacts on extreme energy consumption of different types of buildings, Plos One 10 (4) (2015) e0124413 0124413, doi:10.1371/journal.pone.
[19] M.C. Li, J. Guo, Z. Tian, J. Shi, M.M. Xiong, C. Xiang, Future climate change and building energy demand in Tianjin, China, Build. Serv. Eng. Res. Technol. 35 (4) (2014) 362–375.
[20] V. Martinaitis, D. Bieksa, V. Miseviciute, Degree-days for the exergy analysis of buildings, Energy Build. 42 (2010) 1063–1069.
[21] C. McGilligan, S. Natarajan, M. Nikolopoulou, Adaptive comfort degree-days: a metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates, Energy Build. 3 (2011) 2767–2778.
[22] F.C Meng, M.C. Li, J.F. Cao, J. Li, M.M. Xiong, X.M. Feng, G.Y. Ren, The effects of climate change on heating energy consumption of office buildings in different climate zones in China, Theor. Appl. Climatol. (2017), doi:10.1007/s00704-017-2206-6.
[23] K. Papakostas, T. Mavromatis, N. Kyriakis, Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece, Renew. Energy 35 (2010) 1376–1379.
[24] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (3) (2008) 394–398.
[25] H.S. Qian, S.Q. Yuan, J.L. Sun, Z.H. Li, Relationships between energy consumption and climate change in China, J. Geogr. Sci. 14 (1) (2004) 87–93.
[26] G.Y. Ren, Urbanization as a major driver of urban climate change, Adv. Clim. Change Res. 6 (1) (2015) 1–6.
[27] F.T. Song, Q.F. Zhu, Y. Jiang, Building environment design simulation software DeST (5): generation of the values of the extraneous factors influencing building thermal processes, HV & AC 34 (11) (2004) 52–65.
[28] M. Stathopoulou, C. Cartalis, Daytime urban heat islands from Landsat ETM+ and Coine land cover data: An application to major cities in Greece, Sol. Energy 81 (3) (2007) 358–368.
[29] K.K.W. Wan, D.H.W. Li, D.L. Liu, J.C. Lam, Future trends of building heating and cooling loads and energy consumption in different climates, Build. Environ. 46 (2011) 223–234.
[30] H.J. Wang, Q.Y. Chen, Imapct of climate change heating and cooling energy use in buildings in the United States, Energy Build. 82 (2014) 428–436.
[31] R. Yao, B. Li, K. Steemers, Energy policy and standard for built environment in China, Renew. Energy 30 (2005) 1973–1988.
[32] Y.H. Yau, S. Hasbi, A review of climate change impacts on commercial buildings and their technical services in the tropics, Renew. Sust. Energy Rev. 18 (2013) 430–441.
[33] H.D. Zhang, X.X. Zhang, Z.B. Sun, G.L. Tang, A study on degree-day's change in China in the past fifty years, T. Atmospheric Sci. 33 (5) (2010) 593–599.
[34] H.X. Zhao, F. Magoulès, A review on the prediction of building energy consumption, Renew. Sust. Energy Rev. 16 (2012) 3586–3592.
[35] Y. Jiang, Current building energy consumption in China and effective energy efficiency measures, HV&AC 35 (2005) 30–40.